Mimicking Nature — using nonlinear dynamics and chaos theory to enhance performance and transform naval systems

By Dr. Frank E. Gordon

Scientists are learning what nature has known for years — that nonlinear and chaotic systems can provide improved performance. Biological systems, from the nonlinear electrical control signals in the heart to computational methods in the brain, use nonlinear and chaotic processes to survive. The challenge is to understand and apply these techniques to improve man-made designs.

Mention nonlinearity, noise and chaos to most engineers, and they will tell you that they were taught to design systems to avoid these pitfalls. But a group of Navy scientists at the Space and Naval Warfare Systems Center (SSC) San Diego, working closely with fleet users, is developing multiple systems that take advantage of these properties to significantly improve performance.

In some cases, ***they are providing an order of magnitude increase in performance along with a reduction in cost, size and power requirements.*** The SSC San Diego scientists believe that this technology will be critical for the Navy to fulfill the warfighting challenges of Sea Power 21.

Engineers have known for years that instability helps in the design of high performance aircraft by providing increased maneuverability. In fact, today's jet fighters are so unstable that even the best pilots need the aid of a computer just to fly straight and level. The pilot inputs commands through the control stick to direct the plane, and the computer adjusts the control surfaces to provide the desired response.

Scientists and engineers have also known that most things, including electronic components, mechanical systems, living organisms, and our environment, are inherently nonlinear. Conventional engineering practice has been to design systems to be "linear" devices by limiting the operating range to regimes that exhibit quasi-linear performance.

The owner's manual of a stereo system amplifier, for example, provides plots showing a range over which the output is linear. To avoid the distortion that occurs when the amplifier is turned up too high, users often buy systems with significantly larger power supplies than are required to help ensure distortion-free sound in the listening range. Such designs come at the price of increased size, weight, cost and reduced performance.

Nonlinear dynamics is a relatively new science that traces its recent emergence to a paper published in 1963 by a meteorologist named Ed Lorenz. Lorenz used relatively simple nonlinear equations to mimic weather patterns. While these equations produced results that resembled weather patterns, they also demonstrated that extremely small changes in initial conditions could result in significant changes over time, thus limiting the achievable accuracy of long-term weather predictions.

The often cited example is that of a butterfly flapping its wings in China. Through a connected chain of events, the butterfly's movement in China ultimately results in a hurricane forming in the Atlantic Ocean.

Throughout the 1970s and 1980s, basic research in nonlinear dynamics and chaos theory advanced with little practical application. In the 1980s, the Office of Naval Research (ONR) began a program in nonlinear dynamics under Dr. Michael Shlesinger to promote research that would lead to practical applications.

One of the first applications of interest to the Navy was the development of a dynamic control system for crane barges that allowed the operation of cranes in higher sea-states than was previously possible. Additional research at the Naval Research Laboratory (NRL) focused on the use of chaos theory to encrypt messages for secure communications.

At SSC San Diego, Dr. Adi Bulsara performed basic research and published several papers on stochastic resonance, a phenomenon that takes advantage of the noise and nonlinearity inherent in most sensors to enhance the detection of signals. In the late 1990s, SSC San Diego recognized the potential of nonlinear dynamics to revolutionize warfighting, and embarked on a program to recruit scientists and engineers with backgrounds in nonlinear dynamics to focus on the development of new applications.

Some of the Navy's highest priorities, such

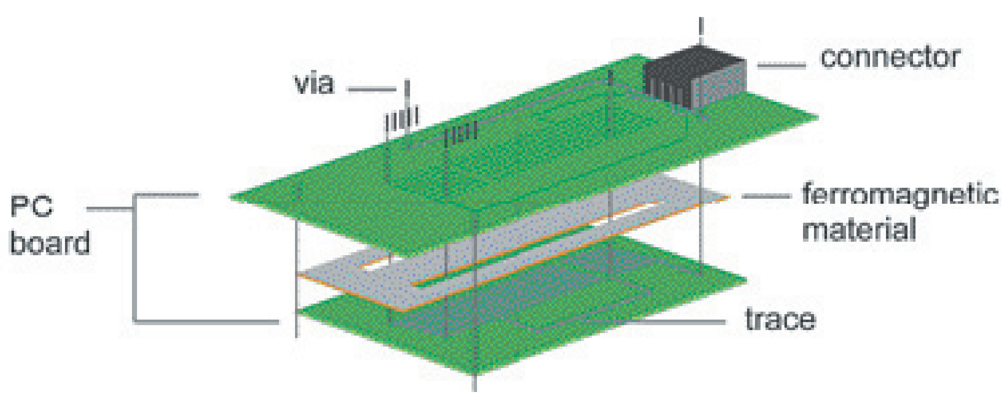

Figure 1.

Exploded diagram detailing the construction of the fluxgate magnetmeter fusing the three-layer construction design. The two outer layers are printed circuit boards with copper wirings printed on them to form the sensing coils and the excitation coils. The middle layer is the special ferromagnetic material shaped to confine the field which helps to enhance the device performance.

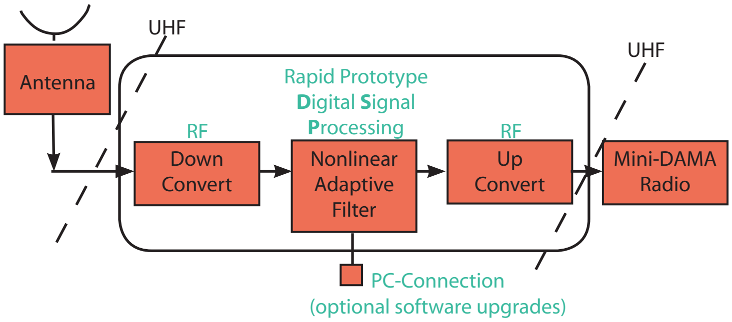

Figure 2. For legacy applications, the nonlinear adaptive filter is placed between the antenna input and the radio. The technology can be incorporated into new radio designs.

as improved communications, increased bandwidth, improved sensors, and more effective countermeasures for dealing with improvised explosive devices, are currently being addressed by nonlinear dynamics technology.

A nonlinear sensor for magnetic detection is one example. For this application, a variant of stochastic resonance is applied in the design of a nonlinear fluxgate magnetometer to detect the metal in objects that range in size from guns and rifles to the hull of a submarine (see Figure 1).

Conventional magnetometers require expensive readout and control electronics that add cost and increase size and power consumption. By contrast, the nonlinear dynamic sensor uses a fundamentally different measurement technique that takes advantage of the full dynamic range of the sensor material.

Increased communication data rates and higher bandwidths are also high priority requirements being addressed by nonlinear dynamics technology. SSC San Diego, ONR and the Submarine Communications Program Office have an innovative solution in development.

A submarine's ultra high frequency satellite communication (UHF SATCOM) antenna is constrained by the size of the submarine mast and must operate a few inches above the ocean surface — where sea states can create dynamic multipath reflections.

Further compounding this environment, UHF SATCOM channels are frequently unusable due to in-band, co-site narrowband interference. For this application, a nonlinear adaptive filter is being designed to remove both the interference and multipath signals, thereby increasing the number of usable UHF SATCOM channels while maximizing the data rate.

For the initial implementation, the filter is installed between the antenna feed and the UHF radio so that it can be adapted for legacy radios (see Figure 2). In laboratory tests using prototype hardware, the nonlinear filter has demonstrated the ability to reclaim unusable SATCOM channels. The system is scheduled to go to sea on a submarine this fall. The goal is to provide the new filter and all associated electronics in a package about the size of a pack of cigarettes at a cost of less than $1,000.

A low cost, phased array antenna is another application that was studied at SSC San Diego under an ONR exploratory development program. The nonlinear, phased array antenna treats the array elements as nonlinear-coupled oscillators that can be made to self-synchronize to form, direct and shape beams.

The design takes advantage of inherent nonlinearity to eliminate expensive phase shifters, wave-guides, and the beam-steering computer and replaces them with low cost ASIC (application specific integrated circuit) radio frequency chips and off-the-shelf parts. By controlling the coupling between elements, a gradient can be formed across the array to both steer and shape beams.

Nonlinear dynamicists at SSC San Diego and its collaborators are exploring additional applications by studying the cells, nervous systems and brains of living organisms. By examining biological systems, dynamicists are finding new functionality in a single transistor.

By recognizing nonlinearities in analog circuits, they are finding ways to perform functions using less complicated systems than conventional "linear" counterparts. This approach is offering new possibilities in the development of sensor, signal processing and decision-making systems.

Hybrid digital and analog electronic circuits, which are compact and low power, are being developed for signal processing applications over a broad range of frequencies. Other designs take advantage of coupled nonlinear oscillators and pattern formation to generate nervous system-like signals.

These designs are being applied to walking robots and other autonomous vehicles. The philosophy of adopting nonlinearities and of examining biological systems is also bridging the gap between hybrid biological and electrically engineered systems.

For example, by modeling neuronal functions on a microchip, hybrid electronic-neuromorphic circuits have been created and have demonstrated that a single leach neuron can perform traditional functions such as addition and multiplication.

More advanced experiments have demonstrated that a hybrid system, consisting of a neuronal network of living neurons grown on a silicone circuit base, was capable of navigating a virtual mouse through a computer-generated videogame-like maze. Concepts like these may redefine the role of computers in our future society.

These are only a few of the potential applications expected to result from nonlinear dynamics technology. Remembering that most systems in use today were designed to avoid the inherent nonlinearities rather than taking advantage of them, this technology holds the potential to provide capabilities far beyond current systems, leading to a transformational revolution as we enter the 21st century.

For more information about SSC San Diego go to http://www.spawar.navy.mil/sandiego/.

Dr. Frank E. Gordon is the head of Navigation & Applied Sciences Department, SSC San Diego.

CHIPS